

Influence of external electric field on the cation transport through the porous membrane

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Transport through porous membranes was studied using ion flows through porous synthetic membranes. It was found that translocation of cations itself occurs primarily by the action of electric forces the origin of which lies in the interaction of ions themselves in solutions around the membrane.

The results also indicate that the translocation of the ion may be continuously controlled and also stopped by the external electric voltage applied on the transport system.

Исследован перенос через пористые мембраны с помощью ионных потоков через пористые синтетические мембраны. Обнаружено, что перемещение катионов происходит первоначально под действием электрических сил, природа которых заключается во взаимодействии ионов, расположенных в растворах вдоль мембраны.

Результаты также указывают на то, что перемещение ионов может быть непрерывно управляемо, а также и остановлено приложением к транспортной системе внешнего электрического напряжения.

The kinetics of ions penetrating membranes may be studied at present by the fluctuation analysis of ions flows through porous synthetic membrane, the conductivity and closely connected dielectric properties of which make them a good transport model studied in the system with composite membranes, such as model systems in which, as in living cells, an accumulation of electrolytes occurs in spite of concentration differences [1—6].

The purpose of this paper is:

1. to present the basic facts and concepts of electrochemistry of membrane transport;
2. to point out the two-sided character of membranes as restrictive barriers and as physicochemical machines, as regards the mechanisms of their function as well as their selective permeability;
3. to show that the electric field influences the concentrations of ions and constitutes the driving force of ion transport; this field should be also considered as a regulating factor of membrane function (*e.g.* the motion of the ions penetrating through membrane) [1—3, 6—9].

Experimental

The experimental investigation into the laws governing the transport phenomenon has been carried out on equipment that utilizes two pairs of Ag/AgCl electrodes, as schematically shown in Fig. 1. An external electric voltage was applied by one pair of electrodes upon the system solution—membrane—solution. The current crossing the membrane was measured simultaneously with the transmembrane electric potential by the multimeter Tesla BM 518 and recorded by the plotter TZ 4100. The transmembrane electric potential was measured by the digital volt-ohm meter MT 100/101 and recorded by a typewriter.

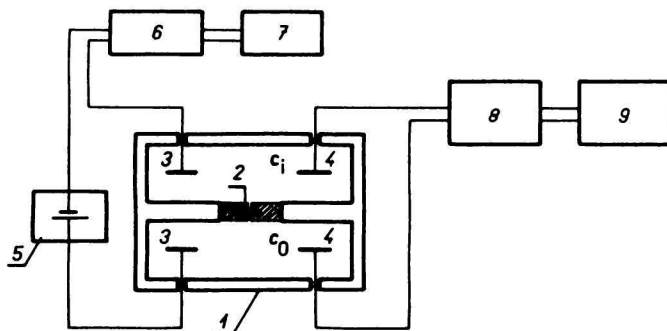


Fig. 1. Layout and connection diagram of measuring circuit.

1. Chamber; 2. membrane holder; 3. electrodes for applying external electric voltage; 4. electrodes for scanning transmembrane voltage, U ; 5. programmable source of direct voltage; 6. microammeter; 7. reading device; 8. digital volt-ohmmeter; 9. reading device.

The concentrations on the outside (c_o) and on the inside (c_i) of membrane were chosen for each measurement: For the inner compartment $c_i(\text{K}^+) = 2.55 \text{ mmol dm}^{-3}$, $c_i(\text{Na}^+) = 4.35 \text{ mmol dm}^{-3}$, $c_i(\text{Ca}^{2+}) = 2.50 \text{ mmol dm}^{-3}$, and $c_i(\text{Mg}^{2+}) = 4.11 \text{ mmol dm}^{-3}$. For the external compartment $c_o(\text{K}^+) = 38.60 \text{ mmol dm}^{-3}$, $c_o(\text{Na}^+) = 65.20 \text{ mmol dm}^{-3}$, $c_o(\text{Ca}^{2+}) = 36.45 \text{ mmol dm}^{-3}$, and $c_o(\text{Mg}^{2+}) = 61.60 \text{ mmol dm}^{-3}$.

The measurements for each pair related values of concentration and applied electric voltage were repeated 5–10 times.

Measurements were carried out on a synthetic nitrocellulose membrane Synpor. This membrane, as it will be shown, has good insulating properties and its pore dimensions are suitable for our aim. Measurements of the polarizing properties of various synthetic membranes were also carried out.

The measure of polarization (relative permittivity ϵ_r) and the measure of electrical energy transformed into heat (loss factor $\text{tg } \varphi$) of the membrane, were estimated by measuring the permittivity and the data needed for calculating the loss angle on Q-meters Tesla BM 311 G and Tesla BM 409 G.

Results and discussion

Dielectric properties of membranes

The results of the polarization measurements of the synthetic membrane are shown in Fig. 2. Fig. 2a illustrates the dependence of ϵ_r on frequency and, for comparison, the dependences of ϵ_r for other synthetic membranes (Millipore U.S. patent and PVC) are presented together with Synpor membranes (Czechoslov. patent). In Synpor 9, Synpor 10, and Millipore membranes ϵ_r declines with the rise of frequency, only in the case of PVC it increases very slightly with the increase of frequency. Loss factor values ($\text{tg } \varphi$) increase with frequency up to the value of $10^{7.5}$ Hz (Fig. 2b). The values of $\text{tg } \varphi$ at frequencies higher than $10^{7.5}$ Hz decline. In the case of PVC $\text{tg } \varphi$ rises along with frequency up to approximately $10^{6.5}$ Hz and drops dramatically at still higher frequencies.

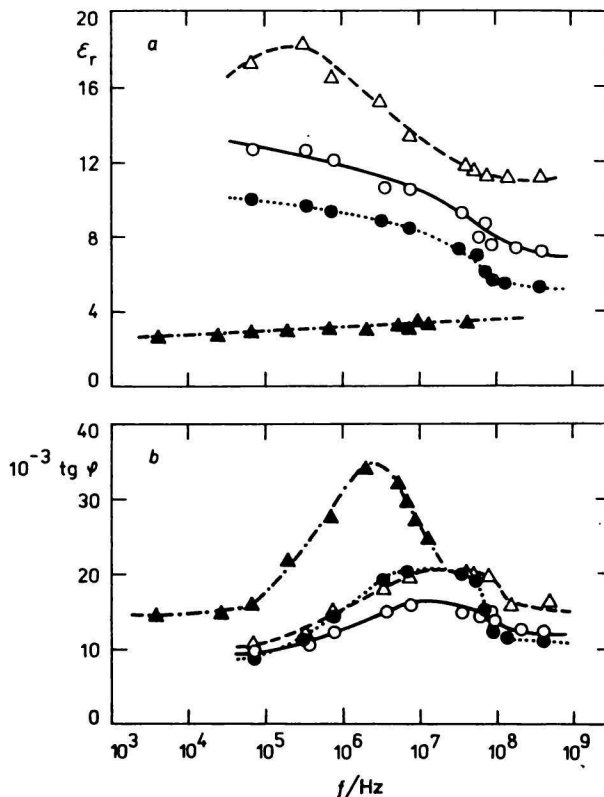


Fig. 2. Dependence of the relative permittivity ϵ_r (a) and of the loss factor $\text{tg } \varphi$ (b) on the electric field frequency for membranes Synpor 9 (O), Synpor 10 (Δ), Millipore (\bullet), and PVC (\blacktriangle).

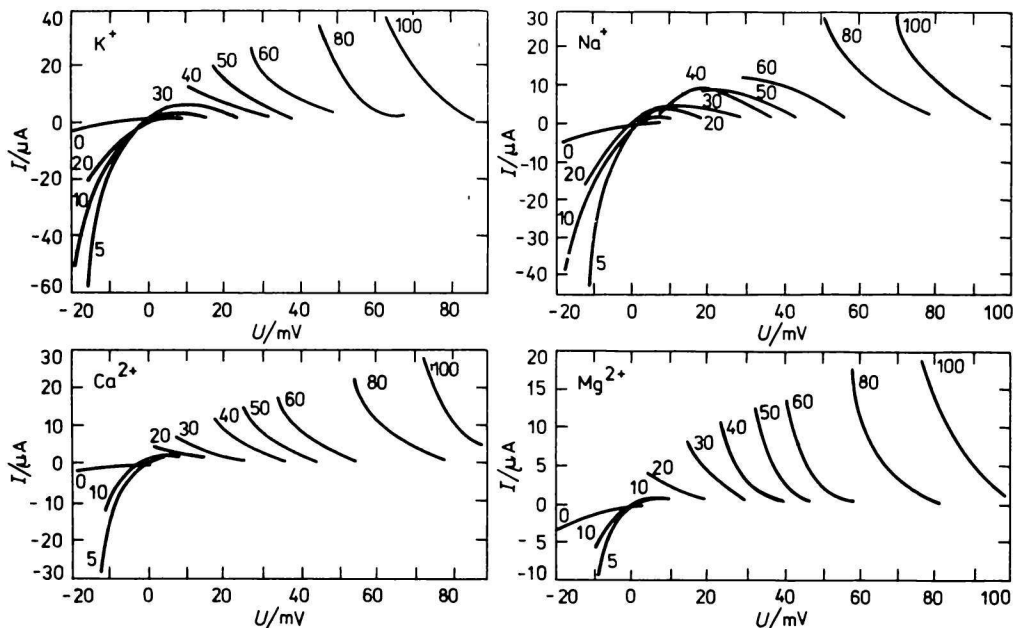


Fig. 3. Changes of current—voltage relations for the synthetic porous membrane Synpor 9 (pore diameter = $0.17\ \mu\text{m}$) for ions of potassium, sodium, calcium, and magnesium, due to the applied external electric voltage (electric voltage is denoted by numerical values U/mV at the curves).

In terms of dielectric properties, the dependences of ϵ_r and $\text{tg}\ \varphi$ on the frequency of the electric field show the similarity of Synpor and Millipore membranes. As far as pore dimensions are concerned, Synpor is more suitable for investigating the phenomenon mentioned in the introduction to this paper. Equally, the dependence $\epsilon_r(f)$ and $\text{tg}\ \varphi(f)$ illustrated in Fig. 2 indicates how the phenomenon observed may be applied to the synthetic membrane. The permittivity of the membrane (Synpor 9) declines with the increase of electric field frequency. The loss factor $\text{tg}\ \varphi$ in this membrane changes within the same frequency range of the electric field from the value of 9×10^3 (at $f = 10^5$ Hz) to the value of 12.5×10^3 (at $f = 10^{8.5}$ Hz). It reaches the maximum value (15.2×10^3) at the frequency of approximately 10^7 Hz. It follows that this membrane does not contain polar molecules.

Values of ϵ_r decline with the frequency of the electric field. The dependence of $\text{tg}\ \varphi$ on frequency indicates that the synthetic membrane is a good insulant.

Influence of electric field on the transport of ions

The results of the investigation of the electric field as a regulating factor of membrane functions are further illustrated in Figs. 3 and 4. The effect of

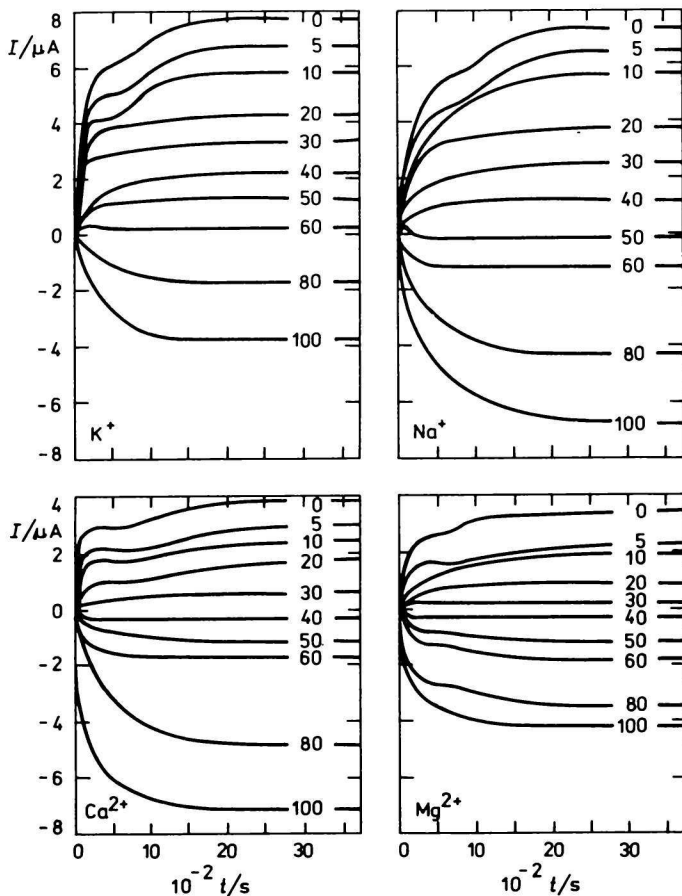


Fig. 4. Dependence of ion flow I_i on time. Numbers at the curves indicate the magnitude of the applied external electric voltage. K^+ , Na^+ , Ca^{2+} , and Mg^{2+} denote elements for which these dependences were measured. The value $I = 0.0$ denotes the state of equilibrium, when the magnitude of external voltage corresponds to the magnitude of the Nernst potential.

external electric voltage upon the direction and magnitude of the ion flow in the system is clearly illustrated by the current—voltage curves in Fig. 3. These curves also characterize the ohmic conductivity of the membrane under the applied constant external electric voltage ($U/mV = 20, 30, 40, 50, 60, 80,$ and 100) upon the membrane. The steepness of these curves characterizes the translocation speed of ions under given conditions.

The current—voltage curves show that the applied electric voltage produces not only changes in ion flow but also a polarization change within this system. This is indicative of the fact that the motion of ions is easily controllable by

applying external electric voltage to the corresponding system. This fact is lucidly illustrated by the dependences of ion flow (I) on time (Fig. 4) under the constant concentration difference around the membrane.

Results illustrated in the figures show that the translocation of the corresponding ion may be continuously controlled or also stopped. It follows that the observed effect of the external electric field upon the ion system around the membrane is a result of the action of forces the magnitude of which is equal to the algebraic sum of the Nernst potential for the corresponding concentration difference and of the applied external electric voltage and that no other source of energy is acting here upon the ion transport.

Further, the results testify that permeation and translocation of ions itself proceeds primarily by the action of the resultant electric forces the origin of which lies in the interaction of ions themselves in solutions around the membrane.

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